

## DEVICE AND METHOD FOR ADJUSTING TWO OBJECT LENSES IN A 4PI-SYSTEM

**[0001]** The present invention relates to a method and device for adjusting the two objective lenses in a 4Pi system of a preferably confocal scanning microscope, in which at least one of the objective lenses is movable relative to the other objective lens.

**[0002]** In 4Pi applications, two objective lenses which are disposed opposite each other with respect to a focal plane and whose optical axes are orthogonal to the focal plane must always be aligned in such a way that their foci meet in exactly one point within the focal plane. High-quality and error-free images can only be produced if the two objective lenses are precisely positioned in this manner.

**[0003]** Presently, very few methods and devices of the type mentioned at the outset have been described. In the known methods, one of the two objective lenses is stationary while the other objective lens is manually moved in the x-, y- and z-directions. By convention, x and y refer to the plane orthogonal to the optical axis, and the z direction is defined to be in the direction of the optical axis. In the known methods, an optical path is coupled out of the 4Pi system, and the interferometric configuration of the 4Pi system is made use of. Specifically, the interferometric image is observed, and the movably disposed objective lens is moved in the x- and y-directions until a zero-order image appears.

**[0004]** The known method is problematic in many aspects. First of all, the procedure described can only be used to adjust the two objective lenses in the x- and y-directions, while the adjustment in the z-direction requires a completely different method. In practice, this means that a user has to switch between the two methods during adjustment, which results in a significant loss of time for the user. Another disadvantage is that the state in which the two objective lenses are precisely adjusted with respect to each other does not remain stable over a longer period of time because of drifts or vibrations. As a result of this, image acquisition is possible just as long as the completed adjustment is stable. In the event of a misalignment, the measurement procedure must be terminated, the two objective lenses must be precisely realigned with each other, and it is only then that the measurement can be continued. Not the least is it attributable to this complicated and time-consuming adjustment, which also requires a high level of knowledge and experience, that no real breakthrough has yet been achieved as far as a routine application of 4Pi microscopy is concerned.

**[0005]** The object of the present invention is, therefore, to design and further refine a method and device of the above type for adjusting the two objective lenses in a 4Pi system, in a way which, on the one hand, allows easy adjustment by the user without any special knowledge and, on the other hand, provides stability of the 4Pi image acquisition over a long period of time.

**[0006]** With the regard to a method for adjusting the two objective lenses in a 4Pi system, the above object is achieved in accordance with the present invention by a method having the features set forth in Claim 1, according to which a method of the type mentioned at the outset is designed in such a way that a reference object is imaged in the pupils of the objective lenses, that a separate Fourier image is formed for each objective lens from the images of the reference object, and that the two Fourier images of the reference object are brought into coincidence by moving at least one of the objective lenses relative to the other.

**[0007]** With the regard to a device for adjusting the two objective lenses in a 4Pi system, the above object is achieved in accordance with the present invention by a device having the features set forth in Claim 14, according to which a device of the type mentioned at the outset is designed in such a way that an illumination device and optical incoupling means are provided for imaging a reference object in the pupils of the objective lenses, that a separate Fourier image can be formed for each objective lens from the images of the reference object, and that the two Fourier images of the reference object can be brought into coincidence by moving at least one of the objective lenses relative to the other.

**[0008]** In accordance with the present invention, first of all, it was realized that in 4Pi microscopy, the simplification of the adjustment of the objective lenses, in particular, is of crucial importance. This simplification is achieved according to the present invention by imaging a reference object in the pupils of the objective lenses, and by forming a separate Fourier image for each objective lens from the images of the reference object. The Fourier image provides an optically very clean instrument that allows the objective lenses to be precisely aligned with each other very simply by moving at least one of the objective lenses relative to the other until the two Fourier images of the reference object, which come from the two objective lenses, exactly coincide with each other. Furthermore, the high sensitivity achieved using the Fourier images allows the two objective lenses to remain precisely aligned

with each other over a long period of time, so that the 4Pi image acquisition may be expected to remain stable over a very long time. Finally, another advantage over the known methods and device is that the objective lenses can be adjusted both in the xy-plane and in the z-direction in substantially the same way. In the method of the present invention, it not even necessary to remove the sample, or to otherwise inconveniently interfere with the microscope itself.

**[0009]** Particularly advantageously, the reference object could have a two-dimensional structure, so that the Fourier image shows illumination distributions both along the x-axis and along the y-axis. To allow for efficient analysis of the Fourier images, and, in particular, in order to obtain the same illumination distribution along the x-axis and along the y-axis in the Fourier image, the reference object could take the form of a cross-shaped aperture.

**[0010]** In order to prevent the illumination beam path and the detection beam path of the 4Pi system, to the extent possible, from being interfered with, it is particularly advantageous for the reference object to be provided outside the 4Pi system.

**[0011]** The illumination device could be provided by a laser light source, which could in particular be an infrared laser light source. It has been shown that infrared illuminating light has almost no influence on microscope image acquisition.

**[0012]** In order to couple the light of the illumination device into the 4Pi optical path, a beam splitter cube and a lens could be provided. The use of a beam splitter cube, preferably a 50/50 beam splitter cube, makes it possible, first of all, that the light of the illumination device can easily be coupled into the 4Pi optical path and, secondly, that the light exiting the 4Pi optical path is not completely reflected back onto the reference object or the illumination device, but can be made available for the analysis of the Fourier images.

**[0013]** In order for the reference object to be imaged in the pupils of the objective lenses, the reference object is advantageously located directly on the beam splitter cube side facing the illumination device.

**[0014]** In a specific embodiment, the Fourier images are imaged by a lens onto a camera, preferably onto a CCD camera. The Fourier images of the reference object, which result from

the two objective lenses, appear in the camera image in a form similar to two pairs of cross hairs, and can therefore be brought into coincidence with each other during an initial coarse adjustment in a particularly simple manner by moving at least one of the two objective lenses relative to the other objective lens.

**[0015]** For a subsequent high-precision fine adjustment, the coincidence of the two Fourier images could be monitored by photodiodes placed in the plane of the Fourier images. In order to allow for easy distinction between the illumination patterns extending horizontally (i.e., in the x-direction) and those extending vertically (i.e., in the y-direction) in the Fourier image, the photodiodes are advantageously disposed in the higher-order space of the Fourier images.

**[0016]** In a preferred embodiment, two photodiodes are disposed in accordance with the two-dimensional structure of the reference object in such a way that one photodiode detects the vertical patterns and the other photodiode detects the horizontal patterns of the Fourier images. Of course, it is also possible to provide more than two photodiodes.

**[0017]** In order to position the objective lenses in the xy-plane, at least one of the objective lenses is moved until a maximum intensity value is reached at each of the two photodiodes. In this case, it is guaranteed that the Fourier images exactly coincide with each other, and that the foci of the two objective lenses meet in exactly one point within the focal plane. The objective lenses' xy-positions that correspond to the respective maximum intensity values of the two photodiodes could be stored in a non-volatile memory for later retrieval.

**[0018]** In order to adjust the objectives along the optical axis, i.e., in the z-direction, at least one of the objective lenses could be moved in the direction of the optical axis in such a way that the sum signal of the photodiodes reaches a maximum intensity value. The sum signal of the two photodiodes becomes maximum exactly when the Fourier images are sharply defined, that is, when the objective lenses are positioned relative to each other in the z-direction in such a way that their foci meet in exactly one point of the focal plane. The objective lenses' z-positions that correspond to the maximum of the sum signal of the two photodiodes could also be stored in a non-volatile memory.

**[0019]** In the event that the signal intensities of the photodiodes differ from the maximum values, which is equivalent to a misalignment of the objective lenses, which may be caused by

drift or vibration, it would be possible to automatically interrupt the measurement. Prior to performing a measurement, limit values could be specified for the intolerable degree of deviation at which to stop the measurement. The interruption of the measurement could be indicated to the user by an audible and/or visual signal.

**[0020]** In a particularly preferred embodiment, the objective lens is automatically readjusted when the signal intensities of the photodiodes deviate from the maximum value. To this end, in particular, the objective lens could be provided with piezoelectric actuators which are controllable as a function of the signal intensities of the photodiodes. It would also be possible for the piezoelectric actuators to be controlled as a function of evaluation data from image processing of the camera images.

**[0021]** The monitoring of the Fourier images and, possibly, the readjustment of the objective lens could be cyclically repeated at regular intervals during a measurement. The measurement could be interrupted for this purpose, but it would also be conceivable for the measurement to continue. In the latter case, it is especially advantageous to log the movements performed by the objective lens during a measurement. Based on the logged data, errors may be corrected during subsequent image processing, as the case may be.

**[0022]** The teaching of the present invention can be advantageously embodied and refined in various ways. In this regard, on one hand, reference is made to the claims that are subordinate to Claim 1 and, on the other hand, to the following description of a preferred exemplary embodiment of the present invention with reference to the drawings. In conjunction with the explanation of the preferred exemplary embodiment of the present invention with reference to the drawings, an explanation is also given of generally preferred embodiments and developments of the teaching.

**[0023]** In the drawing,

**[0024]** FIG. 1 is a schematic view of a 4Pi system and the coupling of a device according to the present invention for adjusting the two objective lenses of the 4Pi system; and

**[0025]** FIG. 2 schematically shows an exemplary embodiment of a device according to the present invention.

[0026] FIG. 1 is a (schematic) view of a 4Pi system of a confocal scanning microscope 1 for examining a sample 2. Scanning microscope 1 includes an illumination beam path 3 of a laser light source 4, a detection beam path 5 of a detector 6, and a component 9 which splits illumination beam path 3 into two illumination beam sub-paths 7, 8 and combines detection beam path 5.

[0027] Illuminating light 10, which is provided by light source 4 and used for illuminating sample 2, is projected through a lens 11 onto excitation pinhole 12. The light passing through excitation pinhole 12 is reflected by a dichroic beam splitter 13 toward a beam deflection device 14. Beam deflection device 14 scans illuminating light beam 10 in two substantially perpendicular directions. The light beam reflected and scanned by beam deflection device 14 hits component 9, where it is split into two sub-beams 15, 16. The illuminating light traveling along the two sub-beams is reflected at mirrors 17, 18 and focused into the same point of sample 1 [sic. 2] from both sides through microscope objectives 19, 20. sub-path The deflection of illuminating light beam 10 via beam deflection device 14 causes a change in position of the illumination foci of the two microscope objectives 19, 20, so that sample 1 [sic. 2] can be illuminated two-dimensionally in the focal plane.

[0028] The detection light, for example, fluorescent, reflected, or transmitted light, emanating from object 1 [sic.2] (which is illustrated only schematically) is collected by the two microscope objectives 19, 20 and travels along illumination beam paths 7, 8 in the opposite direction. The detection light collected by microscope objective 19 (20) is reflected by mirror 17 (18) toward component 9 which combines detection beam path 5. When passing through component 9, the detection light is recombined and directed toward detection pinhole 21 via beam deflection device 14 and dichroic beam splitter 13. The detection light can pass through detection pinhole 21 only if it comes from the illumination focus of the two microscope objectives 19, 20, because, in accordance with the confocal principle, detection pinhole 21 is located in a plane that optically corresponds to the illumination focus of one of the two microscope objectives 19, 20. Similarly, excitation pinhole 12 is located in a plane that optically corresponds to the common illumination focus of the two microscope objectives 19, 20.

**[0029]** In order for the two microscope objectives 19, 20 to be precisely aligned such that the foci of the two microscope objectives 19, 20 meet in exactly one point in the focal plane, use is made of the device denoted by reference numeral 22, which is indicated only schematically in FIG. 1 and shown in greater detail in FIG. 2.

**[0030]** FIG. 2 schematically shows the specific configuration of an exemplary embodiment of a device according to the present invention for adjusting the two microscope objectives 19, 20 in a 4Pi system of a confocal scanning microscope 1. In accordance with the present invention, a cross-shaped aperture 23, which is shown enlarged in the bottom right portion of FIG. 2, is imaged in the pupils of microscope objectives 19, 20. To this end, the illuminating light of an infrared laser light source 24 is directed through an optical fiber 25 and onto a suitable lens system 26, such that cross-shaped aperture 23 is fully and evenly illuminated. Cross-shaped aperture 23 is located on a side of a 50/50 beam splitter cube 27 (BSC Pol Ir), said side facing illuminating light source 24. Via an imaging lens 28, the illuminating light is coupled into the 4Pi system at component 9, such that an intermediate image of cross-shaped aperture 23 is formed in plane 29, and that the cross-shaped aperture is imaged in the pupils of microscope objectives 19, 20. The light exiting the 4Pi system passes through beam splitter cube 27 and is projected through a lens 30 to form a two-dimensional Fourier transform of cross-shaped aperture 23. Due to the beam delivery system described above, a separate Fourier image of cross-shaped aperture 23 is obtained for each of the two microscope objectives 19, 20. An additional lens 31 is used to image the Fourier transforms onto a CCD camera 32.

**[0031]** The optical conditions in plane 33 of the Fourier transforms are shown in detail in the bottom left portion of FIG. 2. There are shown two Fourier images of cross-shaped aperture 23 which are offset from each other; the Fourier image denoted by Fxy1 resulting from the imaging of cross-shaped aperture 23 into the pupil of microscope objective 19, and the Fourier image denoted by Fxy2 resulting from microscope objective 20 accordingly. The situation illustrated in FIG. 2, where the two Fourier images in the form of cross hairs are offset from each other, suggests that the two microscope objectives 19, 20 are not precisely adjusted with respect to each other. For purposes of initial coarse adjustment of the two microscope objectives 19, 20, camera 32 is used in a first step for monitoring while the user brings the two Fourier images Fxy1 and Fxy2 into coincidence by moving objective lens 19 (in the present case, microscope objective 20 is stationary). Once the user has completed this

procedure, he/she can start an automated process in a second step for fine adjustment, which will be described hereinafter:

**[0032]** In plane 33 of the Fourier transforms, two photodiodes 34, 35 are placed in the higher-order space. When microscope objectives 19, 20 are perfectly aligned with each other, i.e., when  $F_{xy1}$  and  $F_{xy2}$  are superimposed, the two photodiodes 34, 35 each indicate a maximum intensity value. Movable objective lens 19, which is capable of being positioned with high accuracy by piezoelectric actuators (not shown), can be iteratively moved in the x- and y-directions until a maximum value is reached at photodiodes 34, 35. In order to detect the direction of movement, objective lens 19 must either be moved beyond the maximum value, or objective lens 19 must be moved in both directions over a sufficient distance until a maximum value is reached. The maximum value is recorded in a non-volatile memory together with the associated position data of objective lens 19. In the event that microscope objectives 19, 20 become misaligned during the measurement, then the stored position data is retrieved from the memory, and corresponding corrective control commands are issued to the piezoelectric actuators. This process can be repeated cyclically.

**[0033]** In order to adjust microscope objectives 19, 20 along the optical axis, i.e., in the z-direction, it is possible to use the information from a sharply defined image of the Fourier images, that is, the sum signal of the two photodiodes 34, 35 is used. Here, use is made of the fact that the Fourier images become increasingly blurred as microscope objectives 19, 20 move away from their precisely adjusted z-positions. If objective lenses 19, 20 are excessively misaligned in the z-direction, then the Fourier images disappear completely. Consequently, a maximum sum signal is obtained when the two objective lenses 19, 20 are precisely adjusted. In order to detect the direction and maximum of the sum signal, the objective lens 19 is slightly moved in the positive and negative z-direction. Once the maximum of the sum signal is found, the associated z-position of objective lens 19 is also stored in a memory. After that, objective lens 19 is moved to the stored position, and then the adjustment of objective lens 19 in the z-direction is also complete. This process can be also repeated cyclically.

**[0034]** Finally, it is particularly emphasized that the exemplary embodiment discussed above is merely intended to illustrate the teaching claimed, but does not limit it to such exemplary embodiment.